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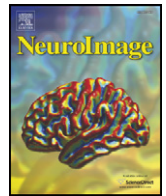
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Tuning down the emotional brain: An fMRI study of the effects of cognitive load on the processing of affective images

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ABSTRACT

The present research examines whether cognitive load can modulate the processing of negative emotional stimuli, even after negative stimuli have already activated emotional centers of the brain. In a functional magnetic resonance imaging (fMRI) study, participants viewed neutral and negative stimuli that were followed by an attention-demanding arithmetic task. As expected, exposure to negative stimuli led to increased activation in emotional regions (the amygdalae and the right insula). Subsequently induced task load led to increased activation in cognitive regions (right dorsolateral frontal cortex, right superior parietal cortex). Importantly, task load down-regulated the brain's response to negative stimuli in emotional regions. Task load also reduced subjectively experienced negative emotion in response to negative stimuli. Finally, coactivation analyses suggest that during task performance, activity in right dorsolateral frontal cortex was related to activity in the amygdalae and the right insula. Together, these findings indicate that cognitive load is capable of tuning down the emotional brain.

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Negative emotional experiences are an inescapable aspect of human life. Although brief episodes of negative emotions can be adaptive (Öhman, 2007), negative emotions may become problematic when they persist over time. Indeed, there is mounting evidence that enduring negative emotional states impair both psychological and physical health (Lyubomirsky et al., 1999; Sapolsky, 1994). It is therefore vital for people to develop ways of effectively dealing with negative emotion.

One important way of dealing with negative emotion consists of minimizing the amount of attentional resources that are devoted to processing negative information (Ochsner and Gross, 2005; Nolen-Hoeksema et al., 1993; Van Dillen and Koole, 2007). More specifically, performing an attention-demanding task has been found to attenuate the emotional impact of negative stimuli (Erber and Tesser, 1992; Erthal et al., 2005; Glynn et al., 2002; Morrow and Nolen-Hoeksema, 1990; Pessoa et al., 2002; Van Dillen and Koole, 2007; *in press*). In recent years, the neural effects of task load on processing of emotional stimuli have begun to receive more systematic attention. Several studies have demonstrated that activity in emotion processing regions of the brain in response to negative emotional stimuli, such as the amygdalae, depend on the availability of attentional resources for processing of these stimuli (Blair et al., 2007; Erk et al., 2007; Okon-Singer et al., 2007; Mitchell et al., 2007; Pessoa et al., 2002; Van

Reekum et al., 2007). For example, in one study, negative visual distracters engaged the amygdalae during participants' judgements whether two bars were like oriented or not (Pessoa et al., 2002), but only when the difference in orientation of two bars was easy to judge. When the orientation of the two bars was difficult to judge, so that the central task became more attentionally demanding, the amygdalae no longer differentiated between the negative and neutral distracters. In another study (Erk et al., 2007), amygdalae responses to negative scenes were smaller when participants concurrently performed a working memory task that was highly rather than moderately demanding.

Although past work has made important progress, it remains unclear precisely how cognitive load influences the emotional brain. One possibility, which has been proposed in prior work, is that cognitive load prevents the processing of the emotional impact of negative stimuli altogether. From this perspective, cognitive load may cause an emotionally relevant stimulus to simply bypass emotional circuits. Given that most prior research relied on demanding distractor tasks that visually competed with emotional information (Erthal et al., 2005; Okon-Singer et al., 2007; Pessoa et al., 2002), cognitive load may have led participants to overlook some of the emotional information.

In support of this notion, Van Reekum et al. (2007) demonstrated that individuals spent less time fixating emotion-relevant stimulus features when they were instructed to reappraise negative visual scenes in less emotional terms than when they were instructed to merely attend to these pictures. This variation in gaze fixation could

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explain a significant amount of the reduction of activation in emotional brain regions during reappraisal compared to passive viewing. Accordingly, attentional deployment strategies (such as an additional task load or attending to non-emotional information) may allow people to manage unwanted emotions even before these emotions have been fully aroused (Gross, 2001).

Another possibility, which is highlighted in the present work, is that task load is capable of down-regulating emotional circuits even after these circuits have been mobilized. This would imply that emotional brain regions operate quite flexibly, in that they can still be modulated by contextual demands even when the initial emotional response has unfolded. In line with this, behavioral research suggests that task load can still modulate emotional processing when the task succeeds, rather than accompanies the emotional stimulus (Erber and Tesser, 1992; Gerin et al., 2006; Glynn et al., 2002; Van Dillen and Koole, 2007). For instance, participants reported less negative feelings in response to negative pictures when they subsequently tried to solve complex rather than simple math equations (Van Dillen and Koole, 2007). Perhaps then, performing a demanding task may similarly down-regulate the unfolding of the emotional brain response to a previously displayed emotional stimulus.

The present research was designed to investigate the neural dynamics by which cognitive load modulates the emotional brain response, even after this response has already been initiated. Importantly, in the present study, the cognitive task followed rather

than accompanied the display of the emotional stimulus. As a consequence, any effects of task load on neural responses to the emotional stimuli could not be accounted for by differences in visual processing strategies, such as controlling visual attention to emotional rather than to non-emotional stimulus features (Van Reekum et al., 2007).

In an experimental study, participants were exposed to neutral or negative emotional pictures, after which they performed an arithmetic task that made varying demands on processing resources (Ashcraft and Kirk, 2001), and rated their emotional state (Fig. 1). Throughout the experiment, participants' brain responses were monitored using functional magnetic resonance imaging (fMRI). We predicted that, relative to exposure to neutral pictures, exposure to negative pictures would activate both negative feelings and emotional brain circuits such as the amygdalae and the insulae (Phan et al., 2002). In addition, we predicted that task load would increase activation in brain regions implicated in cognitive processing, such as the dorsolateral frontal cortex, the superior parietal cortex, and the dorsal occipital cortex (Duncan and Owen, 2000; Rypma et al., 1999).

Most importantly, we hypothesized that cognitive load would modulate subjectively reported emotional states and the activation of emotional brain circuits. That is, we predicted neural activity in regions implicated in emotional processing to decrease with increases in task load. Although the negative pictures should initiate a greater response in emotional brain areas than neutral pictures, we expected that the unfolding of this response over time would be attenuated when participants subsequently performed a highly demanding arithmetic task rather than a moderately demanding arithmetic task. In short, we predicted that task load would modulate the unfolding of the emotional brain response, even after this response was already initiated.

Method

Participants and design

Seventeen volunteers at the VU University Amsterdam (13 women, average age 20) took part in the experiment. All participants were right-handed and native Dutch speakers. The participants did not report any history of neurological or psychiatric problems. The ethical review board of the VU Medical Centre approved of the study and all volunteers provided written informed consent (according to the Declaration of Helsinki) after the study procedure had been explained to them. They were paid €20 for participation. The experimental design was a 2 (task load: high versus low) × 2 (picture valence: neutral versus negative) factorial design, both factors within participants.

Procedure and equipment

Participants were invited to the lab to participate in a brain-imaging experiment. Before starting with the actual experiment, participants were instructed about the experimental set-up. Participants were then led to the scanner-room and positioned supine in the whole-body scanner, where they completed the actual experiment. All stimuli were back-projected onto a screen and viewed by participants through an angled mirror. The experiment consisted of a picture viewing task that contained four blocks of 32 experimental trials (128 trials in total). The order of the blocks was counterbalanced between participants and trials within blocks were displayed in random order. Each trial consisted of a picture followed by an arithmetic task and a mood scale. The pictures were selected from the International Affective Picture System (Lang et al., 2001). Based on published norms (ranging on a scale from 1 [most unpleasant] to 9 [most pleasant]), we selected two sets of 64 pictures, a negative set (pleasantness ratings lower than 2.50) and a neutral set (pleasantness

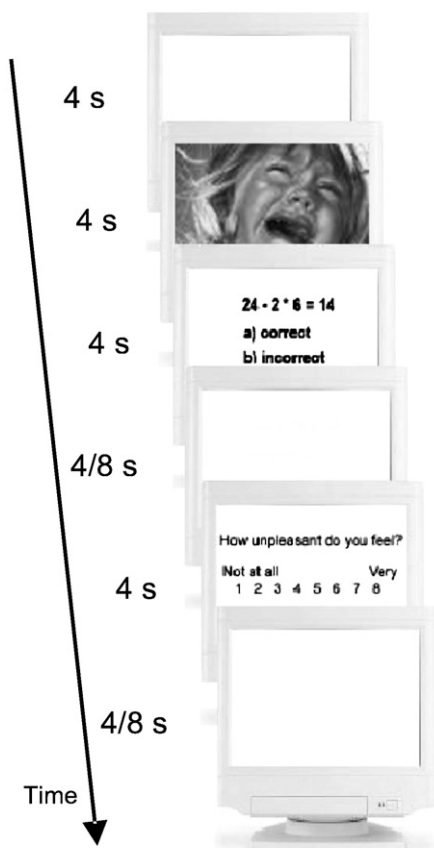


Fig. 1. Schematic depiction of a trial. After a 4 s blank display a picture was presented for 4 s and immediately followed by an arithmetic equation, that consisted of a product or a division combined with a summation or a subtraction, displayed for 4 s. Participants had to judge by a keyboard response whether the equation was correct or not. Pictures were either neutrally or negatively valenced; equations were either complex, such as '24 - 2 * 6 = 14', or simple, such as '5 - 2 = 3'. Following the equation, a blank display was presented for either 4 or 8 s, after which participants indicated on an eight-point scale, ranging from not at all (1) to very much (8), how unpleasant they felt at that moment. Participants had 4 s to make this response. Subsequently, a blank display was again presented for either 4 or 8 s and participants were instructed to relax.

ratings between 4.00 and 5.00). Negative pictures included images of scenes with burn victims, physical assaults, and angry faces. Neutral pictures depicted scenes of people in conversation, scenes of nature or buildings, and neutral faces. The two picture sets were matched as much as possible on dimensions such as living beings, faces, and complexity.

In each trial, a negative or neutral picture appeared on screen for 4 s. After picture presentation, participants had to perform an arithmetic task. The complexity of the task was randomly varied. In half of the trials, the arithmetic task consisted of a more complex equation such as $2 \times 8 + 12 = 28$. These equations always combined a summation or subtraction with a product or division. In the remaining trials, the arithmetic task consisted of a much simpler equation, such as $7 + 2 = 9$. The latter equations only consisted of either a summation or a subtraction. Participants judged whether the equation was correct by pressing a button with either their left or right index finger. Participants had 4 s to make this response. For nine participants, the right button represented the correct response and the left button the incorrect response, while for eight participants this order was reversed.

At the end of each trial, participants rated, with a button response, how unpleasant they felt at that moment (from 1 = *not at all*, to 8 = *very much*). For eight participants, this scale was reversed (ranging from right to left). In between trials, participants were asked to relax. To avoid systematic overlap of BOLD responses within and between trials, the interval between the arithmetic task and the mood scale, as well as the interval between the mood scale and the beginning of the next trial, was set randomly to either 4,000 or 8,000 ms. The duration of each trial accordingly was 20, 24 or 28 s. The onset of each trial was synchronized to the onset of an fMRI volume.

Prior to the presentation of the first block, participants were given a block of 16 practice trials to get familiar with the experimental set-up and the scanner. After the experiment, participants were thanked for their efforts, debriefed, and paid by the experimenter.

A personal computer controlled presentation of the experimental trials and recorded participants' responses. The experimental trials were presented in E-prime (Psychology Software Tools, Inc., Pittsburgh, USA). Participants responded by pressing fiber-optic buttons (Lumitouch Photon Control, Burnaby, Canada).

MRI procedure and analysis

Brain imaging was performed on a 1.5 T Siemens Sonata scanner (Siemens Medical Systems, Erlangen, Germany) equipped with a volume head coil. Functional volumes consisted of 24 near axial slices acquired using an EPI sequence with the following parameters: repetition time = 2 s, echo time = 50 ms, flip angle = 90° , slice thickness = 4.2 mm, slice gap = 0.84 mm, acquisition matrix = 64×64 pixels, in-plane resolution = 3×3 mm. Series of 392 volumes were acquired in each of the four blocks of trials. Images were on-line motion corrected. After the functional session, a three-dimensional structural scan was acquired using a T1-weighted MP-RAGE sequence with the following scanning parameters: repetition time = 2730 ms, echo time = 3.43 ms, inversion time = 1000 ms, flip angle = 7° , 160 sagittal slices, slice thickness = 1 mm, acquisition matrix = 256×224 pixels, in-plane resolution = 1×1 mm.

Preprocessing and statistical analyses of the MRI data were performed using BrainVoyager 2000 software (Brain Innovation, Maastricht, The Netherlands). The first 2 volumes were discarded in order to avoid differences in T1 saturation. Voxel time-series of the remaining volumes were high-pass filtered (0.01 Hz), temporally smoothed (2.5 s FWHM Gaussian kernel), and corrected for slice acquisition times. Finally, volumes were 3D spatially smoothed (6 mm FWHM Gaussian kernel). Each functional run was manually co-registered to the individual 3D structural scan, re-sampled, and transformed into Talairach space (Goebel et al., 2001; Talairach and

Tournoux, 1988). Voxel time series were standardized and corrected for serial correlations.

fMRI data were first analyzed at each voxel (whole brain) and then specifically for a number of regions of interest (ROI's). The initial random-effects whole-brain analysis served to identify brain regions that responded in any way to negative pictures in our task. A multirun/multisubject GLM design matrix was constructed to model the relevant brain responses for each run and participant (Friston et al., 1999). The matrix consisted of regressors predicting hemodynamic responses to each combination of picture valence and task load, as well as the mood scale and possible arithmetic errors. ROI's were defined on the basis of the whole-brain activation obtained in response to negative pictures that were followed either by a simple or a complex arithmetic task. We used a "negative-fixation" contrast because we did not want to miss any region responding to negative pictures. We also included regressors for arithmetic errors and negative mood reports, as these may activate emotional brain regions as well, and may increase the error term if left unexplained. All regressors were convolved with a standard hemodynamic response function, and we analyzed the resulting beta weights at each voxel. The statistical threshold for this random-effects whole-brain analysis was $p = .05$ after Bonferroni correction for multiple comparisons.

The whole-brain analysis revealed activation clusters in a number of regions, such as the bilateral amygdalae, the bilateral inferior insulae, the right dorsolateral frontal cortex and the right superior parietal cortex (see Table 1 for all ROI's). Peaks of activation in each region were located, significant voxels surrounding those peaks were selected, and their time courses were averaged for a subsequent detailed analysis of the shape of the responses at each ROI.

For each ROI and subject, we computed the course of the hemodynamic responses to each valence/load combination by means of a deconvolution analysis. A GLM regressor was assigned to each of 8 fMRI volumes following the onset of a picture, separately for each combination of picture valence and task load. This allowed us to compute the shape of the hemodynamic response without prior assumptions, independent for each condition, ROI and subject. These deconvolved hemodynamic responses were then broken into time frames of 4 s duration (i.e., fMRI volume 1–2, 3–4, 5–6, 7–8), and used in subsequent random-effects analyses of the detailed interactions between task load and picture valence. The motivation for the 4 s (2 volumes) time frames was a compromise between temporal specificity and sufficient signal-to-noise. That is, we wanted to analyze the

Table 1
Statistical regions of interest

Brain region (Brodmann area, hemisphere)	Talairach coordinates (mm)			Volume (ml)
	x	y	z	
Dorsolateral frontal cortex (BA 6/44, right)	40	2	30	0.210
Superior parietal cortex (BA 7, right)	224	−59	53	0.331
Fasciculus uncinatus (BA 34, left)	−28	7	−11	0.353
Dorsal occipital cortex (left)	−22	−79	19	13.979
Dorsal occipital cortex (right)	23	−77	18	13.129
Ventral occipital cortex (left)	−22	−64	−5	30.286
Parahippocampal cortex (left)	−30	−25	−14	0.763
Parahippocampal cortex (right)	34	−19	−16	0.643
Medial anterior temporal cortex (BA 38, right)	34	−4	−23	0.221
Amygdala (left)	−19	−5	−9	0.211
Amygdala (right)	22	−8	−10	0.450
Inferior insula (left)	−31	−1	−9	465
Inferior insula (right)	31	−3	−9	0.173
Pulvinar (left)	−18	−24	0	0.118
Pulvinar (right)	19	−24	0	0.986
Locus coeruleus	0	−30	−28	0.244
Superior colliculus (left)	−6	−24	0	0.934
Superior colliculus (right)	6	−24	0	0.800

Brain areas responding to negative pictures as revealed by the random-effects whole-brain analysis ($p < .05$, corrected).

time courses of the effects of task load in detail, ideally at each volume, but then the number of tests would become large, and the signal-to-noise ratio of each test low. Therefore we grouped 2 volumes, which allowed us to analyze the time courses of the effects at sufficient temporal detail and with sufficient signal-to-noise.

Results

Arithmetic performance

To investigate whether our manipulation of task load was successful, we analyzed participants' correct responses and response times. Analyses of variance (ANOVA's) revealed that participants performed better on simple arithmetic tasks than on complex arithmetic tasks ($M=97\%$ correct, $SD=1.09$ versus $M=84\%$ correct, $SD=5.56$; $F(1, 16)=161.59$, $p<.0001$). Participants were also faster on simple than on complex arithmetic equations, $F(1, 16)=858.38$, $p<.0001$ ($M=1929$ ms, $SD=160$ versus $M=3083$ ms, $SD=145$). These effects confirm that the complex arithmetic equations were more difficult than the simple arithmetic equations. The effects of task complexity did not interact with picture valence for neither participants' correct responses ($F<1$) nor participants' response times ($F<1$).

Self-reported negative emotion

To examine whether task load modulates participants' self-reported negative emotion, we analyzed the effect of both task load (high, low) and picture valence (negative, neutral) on their self-reports, with participants response time differences between complex and simple arithmetic trials as a covariate. As expected, this ANCOVA yielded a significant effect of picture valence, $F(1, 16)=30.39$, $p=.000$. On average, participants reported more negative emotion after trials with negative pictures than after trials with neutral pictures (respectively, $M=4.55$, $SD=1.08$ versus $M=3.15$, $SD=1.14$).

The analysis further yielded the predicted interaction between task load and picture valence, $F(1, 16)=16.50$, $p=.001$. To interpret this effect, we analyzed the effects of task load separately in each valence condition. In line with previous research using the same paradigm (Van Dillen and Koole, 2007), there was no effect of task load in the neutral trials, $F<1$. By contrast, task load had a significant effect in the negative trials, $F(1, 16)=11.54$, $p=.004$. Participants reported less negative emotion when negative pictures were followed by a complex arithmetic equation rather than a simple arithmetic equation ($M=4.40$, $SD=1.07$ versus $M=4.70$, $SD=1.10$). Moreover, response time differences were unable to account for the effects of task load on negative moods, $F(1,15)<1$. Thus, in line with previous findings (Van Dillen and Koole, 2007), task load modulated participants' self-reported negative emotion.

Brain regions involved in both emotion and task-related processes

To investigate whether task load modulated the unfolding of participants' emotional brain responses, we first identified brain regions that responded to negative emotional pictures in our task (see Method section). This yielded a number of areas, such as the bilateral amygdalae, the bilateral inferior insulae, the right dorsolateral frontal cortex and the right superior parietal cortex. In Table 1, the regions of interest (ROI's) are given, with their xyz-coordinates and cluster sizes.

Subsequently, for each region and participant, we computed the course of the hemodynamic response to each picture/load combination by means of a deconvolution analysis, for the first 16 s following picture onset. That is, we estimated the shape of the hemodynamic response by assigning a GLM regressor to each of 8 fMRI volumes following picture onset. In order to assess the timing of the effects of our manipulations more precisely, the hemodynamic responses of the

selected regions were then broken into four time frames of two fMRI volumes each (1–4 s, 5–8 s, 9–12 s, and 13–16 s). These time frames were further tested in subsequent analyses of variance for effects of picture valence and task load.

These subsequent analyses revealed that there were no effects of picture valence or task load during the first time frame following picture onset ($t=1-4$ s). Activation in response to the neutral and negative pictures peaked at time=6 s after picture onset (see Fig. 2), which corresponds to the delay of the hemodynamic response. Analyses of variance of the responses during the corresponding time frame ($t=5-8$ s) revealed that, at this point, all regions of interest (except for the locus coeruleus and parahippocampal cortex) responded more strongly to negative pictures than to neutral pictures (all $p<.05$). Initially, negative pictures thus engaged these brain regions to a greater degree than neutral pictures. The results of these analyses are given in Table 2.

Because the task was presented 4 s after picture onset, effects of task load on the response to the picture would be expected at about 10 s and onwards. In line with this, activation in cognitive processing regions, such as the right dorsolateral frontal cortex, peaked at time=10 s, e.g. during the third time frame ($t=9-12$ s; see Fig. 2). Moreover, if task load indeed modulates the temporal unfolding of emotional responses, this may imply an interaction effect between picture valence and task load on participants' brain activity during this time frame. We indeed found statistically significant interactions between picture valence and task load in several regions during the third time frame ($t=9-12$ s) in right dorsolateral frontal cortex ($F(1, 16)=4.69$, $p=.046$), right superior parietal cortex ($F(1, 16)=5.28$, $p=.035$), the left dorsal occipital cortex ($F(1,16)=5.16$, $p=0.037$), the left amygdala ($F(1, 16)=4.74$, $p=0.045$), the right amygdala ($F(1, 16)=4.82$, $p=.043$), and the right inferior insula ($F(1, 16)=7.70$, $p=.014$) (see Table 3 for an overview).

The effect of task load on brain responses to negative pictures

Recall that we predicted neural responses in emotion regions to negative pictures to be attenuated when followed by a complex task (high load) rather than a simple task (low load), while we expected neural responses in cognitive processing regions to display the opposite pattern. To test these predictions, we directly compared the responses to negative pictures followed by either a complex or a simple arithmetic task in the regions that showed interactions between picture valence and task complexity in the remaining two time frames following task onset (i.e. the third and the fourth time frame). Note that these comparisons result in a positive t -value if the response is greater in the high load than the low load trials, and a negative t -value if the response is greater in the low load trials.

During the third time frame ($t=9-12$ s), the left amygdala ($t(16)=-2.91$, $p=.010$) and the right amygdala ($t(16)=-1.97$, $p=.066$) showed weaker responses to negative pictures followed by a complex task rather than a simple task. During the fourth time frame ($t=13-16$ s), the left amygdala ($t(16)=-4.29$, $p=.001$), right amygdala ($t(16)=-5.11$, $p=.0001$), and right insula ($t(16)=-2.25$, $p=.039$) showed weaker responses to negative pictures followed by a complex task rather than a simple task (see Table 4). These regions are known to be involved in the processing of emotional stimuli (Ochsner et al., 2004; Phan et al., 2002). Thus, increased cognitive load led to reduced activation in emotion circuits.

During the third time frame ($t=9-12$ s), right dorsolateral frontal cortex ($t(16)=7.94$, $p<.0001$), right superior parietal cortex ($t(16)=6.62$, $p<.0001$), and left dorsal occipital cortex ($t(16)=5.01$, $p=.0001$) showed greater activation to negative pictures followed by a complex task rather than a simple task. During the fourth time frame ($t=13-16$ s), right dorsolateral frontal cortex ($t(16)=3.43$, $p=.003$), right superior parietal cortex ($t(16)=2.43$, $p=.027$), and left dorsal occipital cortex ($t(16)=2.52$, $p=.023$) showed greater activation to negative

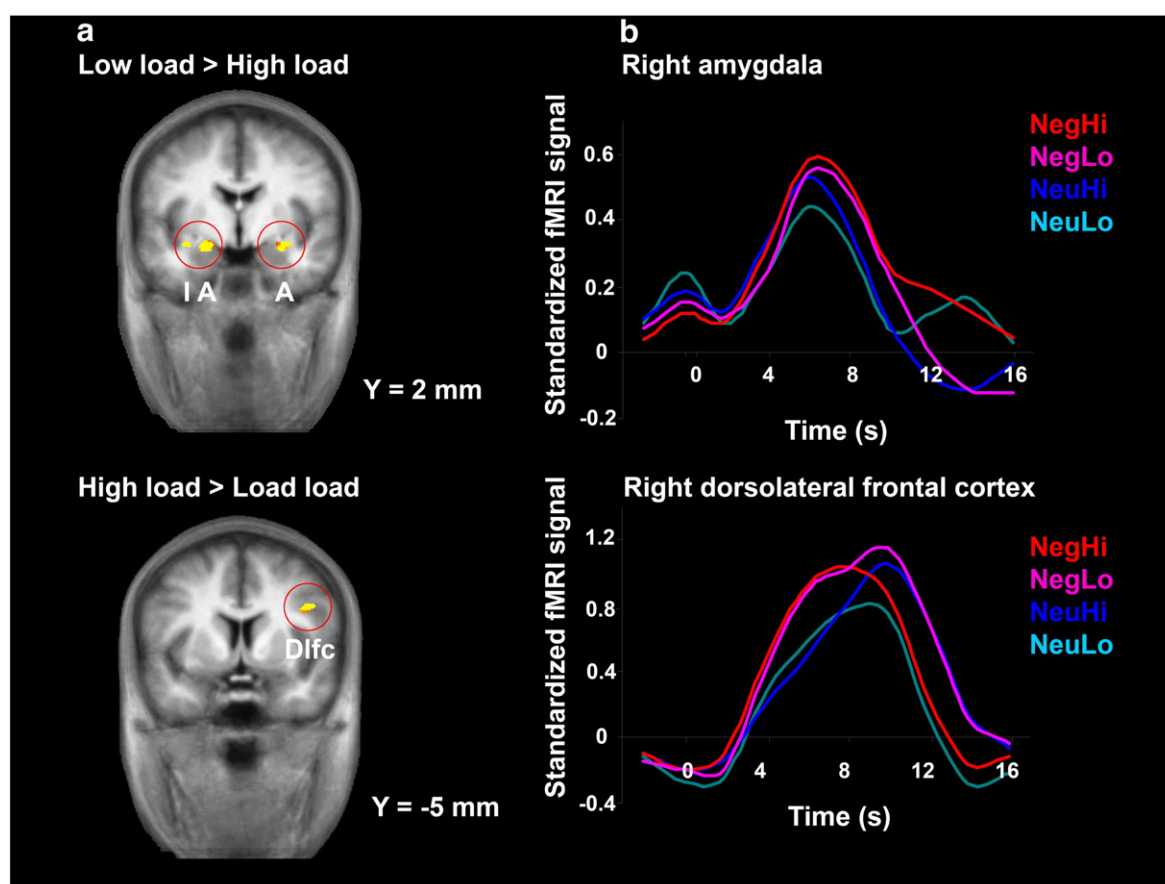


Fig. 2. (a) Two coronal views of the averaged brain ($n=17$) in Talairach space on which areas are displayed that responded significantly to negative pictures ($p < .05$, corrected for multiple comparisons) and in which activity was either greater when task load was low compared to high (upper row; amygdalae [A] and right inferior insula [I]), or in which activity was greater when task load was high compared to low (lower row; right dorsolateral frontal cortex [Dlfc]). (b) Deconvolved averaged timecourses of the brain responses in the right amygdala and right dorsolateral frontal cortex for each trial type; negative (Neg) or neutral (Neu) pictures that were followed by either a high (Hi) or a low (Lo) load task. Picture onset was at time = 0 s, task onset was at time = 4 s. Due to the hemodynamic delay, effects of pictures valence are observed from time = 6 s onwards and effects of task load from time = 10 s onwards.

pictures followed by a complex task rather than a simple task (see Table 4). These regions are known to be involved in cognitive processing and to respond to increasing task demands (De Fockert et al., 2001; Duncan and Owen, 2000; Prabhakaran et al., 2000; Rypma et al., 1999). Thus, as

Table 2

Regions of interest showing a greater response to negative than to neutral pictures between 5 and 8 s after picture onset ($p < .05$)

Brain region (Brodmann area, hemisphere)	Talairach coordinates (mm)			Volume (ml)	F_{val} 5–8 s
	x	y	z		
Dorsolateral frontal cortex (BA 6/44, right)	40	2	30	0.210	61.56*
Superior parietal cortex (BA 7, right)	24	-59	53	0.331	13.63*
Fasciculus uncinatus (BA 34, left)	-28	7	-11	0.353	43.23*
Dorsal occipital cortex (left)	-22	-79	19	13.979	12.13*
Dorsal occipital cortex (right)	23	-77	18	13.129	8.63
Ventral occipital cortex (left)	-22	-64	-5	30.286	6.47
Medial anterior temporal cortex (BA 38, right)	34	-4	-23	0.221	8.53
Amygdala (left)	-19	-5	-9	0.211	51.89*
Amygdala (right)	22	-8	-10	0.450	5.32
Inferior insula (left)	-31	-1	-9	465	10.94*
Inferior insula (right)	31	-3	-9	0.173	5.32
Pulvinar (left)	-18	-24	0	0.118	25.89*
Pulvinar (right)	19	-24	0	0.986	8.31
Superior colliculus (left)	-6	-24	0	0.934	77.66*
Superior colliculus (right)	6	-24	0	0.800	57.21*

Note. F_{val} = F -value of picture valence, all negative > neutral. Degrees of freedom are 1 and 16, * $p < .01$.

expected, performing complex arithmetic sums engaged brain regions that support cognitive processes.

Recall that we found an effect of task complexity on participants' response times. To investigate whether the effects of task load could be attributed to response time differences between the complex and the simple arithmetic equations, we repeated the analyses with participant's response time difference between complex and simple trials as a covariate. These analyses did not reveal any differential findings, except for the left amygdala during the third time frame ($t=9-12$ s). When entered as a covariate, response time differences partially accounted for the effect of task complexity on left amygdala responses, $F(1,15)=7.22$, $p=.017$. However, a 2 (task complexity)

Table 3

Regions of interest showing a picture valence \times task load interaction between 9 and 12 s after picture onset

Brain region (Brodmann area, hemisphere)	Talairach coordinates (mm)			Volume (ml)	F_{int} 9–12 s
	x	y	z		
Dorsolateral frontal cortex (BA 6/44, right)	40	2	30	0.210	4.69
Superior parietal cortex (BA 7, right)	24	-59	53	0.331	5.28
Dorsal occipital cortex (left)	-22	-79	19	13.979	5.16
Amygdala (left)	-19	-5	-9	0.211	4.74
Amygdala (right)	22	-8	-10	0.450	4.82
Inferior insula (right)	31	-3	-9	0.173	7.70

Note. F_{int} = F -value of picture valence \times task load interaction. Degrees of freedom are 1 and 16, $p < .05$.

Table 4

Regions of interest displaying an effect of task load on responses to negative pictures during the third and fourth time frame ($t=9-12$ s, and $t=13-16$ s, respectively)

Brain region (Brodmann area, hemisphere)	Talairach coordinates (mm)			Volume (ml)	T_{neg}	
	x	y	z		9–12 s	13–16 s
High load > low load						
Dorsolateral frontal cortex (BA 6/44, right)	40	2	30	0.210	7.94**	3.43**
Superior parietal cortex (BA 7, right)	24	-59	53	0.331	6.62**	2.43*
Dorsal occipital cortex (left)	-22	-79	19	13.979	5.01**	2.52*
Low load > high load						
Amygdala (left)	-19	-5	-9	0.211	-2.91*	-4.29**
Amygdala (right)	22	-8	-10	0.450	-1.97†	-5.11**
Inferior insula (right)	31	-3	-9	0.173	-1.11	-2.25*

Note. T_{neg} = t -value of effect of task load after negative pictures; with positive t meaning greater response to high than to low load, and negative t meaning greater response to low than to high load. Degrees of freedom = 16, ** $p < .01$, * $p < .05$, † $p < .1$.

ANCOVA analysis of the brain responses in the negative trials still revealed a significant effect for task complexity ($F(1,16)=5.01$, $p=.040$). Accordingly, the effects of task complexity could not be fully accounted for by response time differences but instead may be the result of the differential cognitive involvement in the task.

Interrelation of brain regions involved in emotion and task processing

We examined the interrelations of neural activity in emotion regions (i.e. the amygdalae and right insula) on the one hand and regions implicated in the arithmetic task (i.e. right dorsolateral frontal cortex, right superior parietal cortex, left dorsal occipital cortex) on the other hand. To this end, we first computed an index of the amount of modulation of picture valence by task load. We did this by calculating the difference between responses to negative pictures followed by a simple task and neutral pictures followed by a simple task, minus the difference between responses to negative pictures followed by a complex task and neutral pictures followed by a complex task, separately for each participant, ROI, and fMRI time frame. Note that because of the double subtraction, the sign of the task load effect is lost. We then correlated these indices of the modulation of the valence effect across participants between ROIs, separately for each time frame.

We found that activation in left amygdala correlated with activation in right dorsolateral frontal cortex ($r=.52$, $p=.027$) and left dorsal occipital cortex ($r=.47$, $p=.049$) during the third time frame ($t=9-12$ s) following picture onset. Moreover, activation in right inferior insula correlated with activation in right dorsolateral frontal cortex during the third (displaying a trend; $r=.43$, $p=.075$) and fourth time frame following picture onset ($r=.47$, $p=.049$). Whereas activation in right dorsolateral frontal cortex and left dorsal occipital cortex was greater in response to high compared to low task load, activation in limbic regions was smaller in response to high compared to low task load (see previous section, Table 4 and Fig. 2). In line with predictions, there thus seemed to be a systematic relationship between activity in regions implicated in emotional processing (amygdala, right insula) and activity in regions implicated in cognitive processing (right dorsolateral frontal cortex, left dorsal occipital cortex) which is consistent with the idea that these systems operate in a coordinated manner (Pessoa, 2008). However, given that we could not control for collinearity and that the reported correlations were only moderately strong, we suggest these coactivation findings be interpreted with caution.

Gender differences

Research has reported gender differences in brain responses to standardized emotional stimuli (Canli et al., 2002; Mackiewicz et al.,

2006; Wrase et al., 2003). To investigate any effects of gender, we repeated all above analyses for the responses of the female participants only ($n=13$). Excluding the male participants from the analyses did not alter the observed response patterns.

Discussion

The present research examined how cognitive load modulates the unfolding of the emotional brain response. Importantly, in the present paradigm, the emotional stimulus and the cognitive load were presented in succession. Thus, participants solved an arithmetic equation following each neutral or negative picture. This temporal separation made it possible to investigate the dynamic unfolding of the interplay between cognitive and emotional neural structures. Moreover, by inducing cognitive load following rather than during picture display, we could examine the effects of cognitive load on the unfolding of the emotional brain response, while controlling for differences in visual processing strategies (Van Reekum et al., 2007). Previous research has proposed that task load may 'short-circuit' emotional processing in the brain, for example by deploying visual attention, such that activity in emotional brain regions is inhibited altogether. In the present research, however, we find that even when emotional circuits have already been engaged, performing a demanding task may still attenuate processing in the emotional brain.

The present findings indicate that both regions involved during the arithmetic task (right dorsolateral frontal cortex, right superior parietal cortex and left dorsal occipital cortex) and emotion regions (bilateral amygdalae, right insula) initially showed greater activity in response to negative pictures than in response to neutral pictures. Consistent with previous work (Cohen et al., 1997; Prabhakaran et al., 2000), high task load further resulted in an increase in activity in the regions implicated in the arithmetic task (right dorsolateral frontal cortex, right superior parietal cortex, dorsal occipital cortex). More importantly, task load also resulted in a decrease in brain regions involved in emotion processing (bilateral amygdalae, right insula). Finally, during task performance, activity in right dorsolateral frontal cortex, and, to a lesser extent, left dorsal occipital cortex, was related to activity in emotion regions (left amygdala, right insula). Together, these findings suggest that emotional and cognitive circuits in the brain operate in a coordinated manner to deal with changing task demands.

The present findings go beyond a simple reciprocal modulation of cognitive and emotion circuits in the brain, in that increases in activity in cognitive brain regions not necessarily resulted in decreases in activity in emotional brain regions. That is, during picture display, activity in right dorsolateral frontal cortex, right superior parietal cortex, and left dorsal occipital cortex, as well as limbic regions, i.e. the bilateral amygdalae and the insulae, was greater in response to negative pictures than to neutral pictures. Only when participants performed the arithmetic equations neural responses in these regions began to differentiate. Whereas activity in cognitive regions increased even more in right dorsolateral frontal cortex, right superior parietal cortex, and left dorsal occipital cortex, performing the arithmetic equations resulted in a decrease in neural activity in limbic regions.

Coactivation analysis revealed that these opposite response patterns in higher cortical versus limbic regions were related, suggesting that the more right dorsolateral frontal cortex and left dorsal occipital cortex were engaged by the arithmetic task, the more emotional brain responses were attenuated. This is in line with previous research reporting a suppression of activity in limbic regions by (frontal) cortical regions during higher cognitive processes (Drevets and Raichle, 1998). However, given the correlational nature of our analyses, the causality of these relationships cannot be determined. We therefore suggest the present findings be interpreted with caution.

In line with previous findings (Erk et al., 2007), right dorsolateral frontal cortex was "shared" by task-related and emotional processing, such that this region was particularly engaged when negatively

valenced pictures were followed by complex arithmetic tasks. Accordingly, our results reveal an integration effect for processing negative emotion and task load in right dorsolateral frontal cortex. One potential explanation for these findings is that the right dorsolateral frontal cortex is engaged more with increasing task load, in order to sustain priority to processing of the central task at the cost of the further processing of emotionally salient, but task irrelevant negative stimuli (see Erk et al., 2007, for a similar argument). Theorists have proposed that the lateral frontal/prefrontal cortex may function as a key neural substrate of the central bottleneck of information processing (Dux et al., 2006; Herath et al., 2001; Marois and Ivanoff, 2005). As such, the lateral frontal cortex may be critical for mental operations such as cognitive control, decision-making, and modality-independent selection of task-relevant information (Badre et al., 2005; Brass et al., 2005; Bunge et al., 2003). The present findings suggest that the role of the lateral frontal cortex in controlling information processing may extend beyond the cognitive domain, and may similarly control the processing of emotional information.

Cognitive emotion regulation strategies may build upon more general information processing systems such as working memory and cognitive control that typically engage (frontal) cortical regions such as the dorsolateral frontal cortex, the superior parietal cortex and the dorsal occipital cortex (Ochsner and Gross, 2008). Indeed, a recent study revealed a role of the lateral frontal cortex in inhibiting emotional distraction in healthy adults during a working memory task (Johnson et al., 2005; Dolcos and McCarthy, 2006). Performing a working memory task engaged the lateral frontal cortex to a greater degree when the participants were distracted by negative emotional pictures rather than neutral or scrambled pictures. Moreover, participants who displayed greater activity to emotional distracters in the lateral frontal cortex judged emotional distracters as less distracting and less emotional.

The present findings potentially have important implications for psychopathologies that are characterized by both emotional and cognitive deficits, like depression and anxiety (Harvey et al., 2005; Luu et al., 1998; Mayberg et al., 1999). Emotional stimuli can have a lasting effect on amygdala activity (Cuthbert et al., 2000), specifically in depressed individuals (Siegle et al., 2002). Moreover, research has shown that people are inclined to ponder over a negative experience, which may subsequently intensify and prolong people's negative emotional states (Nolen-Hoeksema et al., 1993). Placing people in a quiet environment in order to let them 'cool down' from an emotional response may therefore not necessarily result in a more neutral state of mind. Although more research is needed in this area, it is conceivable that cognitively demanding tasks may eventually be used as a therapeutic tool. Having people perform an engaging task may alleviate the intensity of acute emotional responses, such that people become more receptive to long-term therapeutic interventions.

More broadly speaking, the present work attests to the close coordination between cognitive and emotional functioning. Whereas both cognitive and emotional brain circuits are involved in processing negative pictures, our findings demonstrated that further engagement of cognitive circuits by a subsequent task go hand in hand with a decrease in activity in emotional circuits (Drevets and Raichle, 1998; Keightley et al., 2003; Mayberg et al., 1999), especially when processing load of the task is high. Depending on the threats and challenges that people face, cognitive and emotional systems are recruited in a flexible manner, such that people can deal effectively with the ever changing demands of their environment.

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